DEVELOPMENT OF HYBRID FORCE-POSITION CONTROLLER FOR ULTRASOUND-GUIDED BREAST BIOPSY ROBOTIC SYSTEM

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For my beloved parents

& my dearest partner, Nurasyeera.

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ABSTRACT

Conventional ultrasound-guided breast biopsy (UGBB) procedure is commonly performed to assess abnormal masses within the breast. It requires a radiologist to handle multiple devices at once, which could reduce the abilities in performing such procedure resulting in radiologist's fatigue, compromised breast tissue due to multiple insertions and susceptibilities to pneumothorax complication for the patient. Previous studies have reported that many of the restrictions associated with handheld minimally invasive methods were tackled when physician assist instruments were used. Therefore, the purpose of this research is to assist radiologist in conventional UGBB procedure by introducing a semi-automated robotic system to maintain desired contact force between the ultrasound transducer and the breast. For that reason, a hybrid force/position controlled UGBB robotic system has been developed in simulation environment. The UGBB robotic system involves a 5 degree of freedom (DOF) articulated robot arm to control the transducer movement, a force/torque (F/T) sensor system to measure the contact force, an ultrasound machine to view the inside structure of the breast tissue and a computer-based control system. As such, the RV-2AJ robotic arm has been modelled with its positional accuracy of almost 100%. A breast model based on a medical grade breast phantom has been established with a mean error of 0.69% by using black-box modelling approach. Motion disturbance from human respiration has been explored as well since it plays a significant element that would affect the stability of the system to constantly maintain low contact force on the breast. Finally, intelligent Fuzzy-PID hybrid force/position controller has been successfully established to maintain low contact force on identified breast stiffness characteristics. The overall hardware-based simulation shows promising outcomes with almost no overshoot, fast rise time, high robustness and stability on different environment condition. In conclusion, the success of this work serves as significant foundations for long-term related research, especially in the development of UGBB robotic system and approaches of force control mainly for human-robot interaction.

ABSTRAK

Prosedur konvensional biopsi payudara secara *ultrasound* (UGBB) dijalankan secara meluas untuk menilai ketumbuhan yang tidak normal di dalam payudara. Ianya memerlukan pakar bedah untuk mengendalikan pelbagai alat pada satu-satu masa, yang mana boleh mengurangkan keupayaan pakar bedah dalam melakukan prosedur tersebut, mengakibatkan keletihan kepada pakar bedah, dan menjejaskan integriti struktur tisu payudara akibat kekerapan suntikan jarum biopsi. Kajian terdahulu telah melaporkan bahawa banyak sekatan yang berkaitan dengan kaedah pandu tangan invasif secara minimum dapat ditangani dengan menggunakan alat bantuan kepada doktor. Oleh itu, tujuan penyelidikan ini adalah untuk membantu ahli radiologi dalam prosedur konvensional UGBB dengan memperkenalkan sistem robotik separa automatik untuk mengekalkan daya sentuhan yang dikehendaki antara transduser *ultrasound* dan payudara. Atas sebab itu, satu sistem robot hibrid daya/posisi UGBB telah dibangunkan dalam persekitaran simulasi. Sistem robot UGBB tersebut melibatkan 5 darjah kebebasan (DOF) untuk mengawal pergerakan transduser, sistem deria daya/kilas (F/T) untuk mengukur daya sentuhan, mesin *ultrasound* untuk melihat struktur dalaman tisu payudara, dan sistem kawalan berasaskan komputer. Dengan itu, sistem robot RV-2AJ telah dimodelkan dengan ketepatan posisinya menghampiri 100%. Model payudara berdasarkan payudara silikon gred perubatan juga telah ditubuhkan dengan kesilapan min 0.69% dengan menggunakan pendekatan permodelan kotak hitam. Gangguan pergerakan dari pernafasan manusia juga telah dibangunkan memandangkan ianya memainkan peranan penting dalam memberi kesan kepada kestabilan sistem untuk mengekalkan tekanan yang rendah terhadap payudara. Akhir sekali, pengawal hibrid daya/posisi telah berjaya ditubuhkan untuk mengekalkan daya sentuhan rendah terhadap kekerasan payudara silikon yang dikenal pasti. Keseluruhan simulasi berasaskan perkakasan menunjukkan hasil yang memberangsangkan dengan hampir tiada lebihan respon, masa kenaikan yang pantas, kekukuhan dan kestabilan yang tinggi dalam keadaan persekitaran yang berbeza.

Kejayaan kajian ini merupakan landasan penting bagi penyelidikan jangka panjang, terutamanya dalam pembangunan sistem robot UGBB dan pendekatan kawalan daya untuk interaksi antara robot dan manusia.

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LIST OF SYMBOLS AND ABBREVIATIONS

°	-	Degree
θ	-	Theta
%	-	Percentage
2D	-	Two-Dimensional
3D	-	Three-Dimensional
ACF	-	Autocorrelation Function
ARX	-	Auto Regression Exogenous
ASR	-	Age-Standardized Rate
CAD	-	Computer-Aided Design
CCF	-	Cross Correlation Function
CTV	-	Clinical Target Volume
D-H	-	Denavit-Hartenberg
DC	-	Direct Current
DCBF	-	Digital Continuous Beam Former
DLL	-	Dynamic-Link Library
DMS	-	Dead Man's Switch
DOF	-	Degree of Freedom
F-PID	-	Fuzzy PID
FL	-	Fuzzy Logic
F/T	-	Force/Torque
FES	-	Functional Electrical Stimulation

FIS	-	Fuzzy Inference System
FNAC	-	Fine Needle Aspiration Cytology
FOV	-	Field of View
g	-	Gram
GUI	-	Graphical User Interface
Hz	-	Hertz
IAE	-	Integral of Absolute Error
IARC	-	International Agency for Research on Cancer
ILC	-	Iterative Learning Control
ITAE	-	Integral of Time Absolute Error
kg	-	Kilogram
LAD	-	Left Anterior Descending
LED	-	Light-Emitting Diode
mm	-	Millimeter
MRC	-	Modified Rate Control
ms	-	Milliseconds
N	-	Newton
N-mm	-	Newton-millimeter
NARX	-	Nonlinear ARX
NCR	-	National Cancer Registry
NNARX	-	Neural Network with ARX
PC	-	Personal Computer
PFC	-	Predictive Functional Control
PI	-	Proportional Integral
PID	-	Proportional, Integral and Derivative
PM	-	Pneumatic Muscles

RLS	-	Recursive Least Square
RSS	-	Robot Simulation Software
s	-	Seconds
SD	-	Standard Deviation
UGBB	-	Ultrasound-Guided Breast Biopsy

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CHAPTER 1

INTRODUCTION

The International Agency for Research on Cancer (IARC) reported in 2012 that breast cancer is the second most common cancer in the world and the most frequent cancer among women (Ferlay et al., 2015). It was estimated that 1.67 millions new breast cancer cases were diagnosed and was ranked as the fifth cause of death (522,000 deaths) from overall cancers. In Malaysia, the IARC estimated an Age-Standardized Rate (ASR) of breast cancer as 38.7 per 100,000 with 5410 new cases in 2012.

According to the 5-year Malaysian National Cancer Registry (NCR) report for new cancers diagnosed from 2007 to 2011, breast cancer in Malaysia accounted to the most common cancer for all residents by 17.7% and the most frequent cancer among women by 32.1% (Ministry of Health, 2016). Overall, Malaysian women have poor survival from breast cancer due to poor understanding of the risk factors, symptoms and methods for early detection of breast cancer (Yip et al., 2014). Otherwise, it is approximated that half of the deaths due to breast cancer could be prevented, considering that survival rates essentially depend on the timely discovery of the disease, which is at the early stage of the unregulated cell growth.

As stated by Bruening et al. (2009), women diagnosed with initial phases of the breast cancer have a 5-year survival rate of making a full recovery. The standard diagnostic procedure is denoted as triple-assessment, which basically comprises of three medical inspections to attain great assurance in the diagnosis. They are palpation (self-examination or by a specialist), breast imaging (a combination of mammography and ultrasound) followed by fine needle biopsy if necessary.

Two notable approaches for breast biopsy include needle biopsy and open excisional biopsy (Mayo Clinic, 2014). Image-guided needle biopsy is more appealing because it is less traumatic, produces little or no scar (Fine & Staren, 2006; Killebrew & Oneson, 2006; Koskela et al., 2006), allows quicker recovery, and substantially low cost than open surgical biopsy (Zuiani et al., 2005). The procedure is an invasive assessment that incorporates in acquiring the sample cells from the suspicious lump. The obtained cells are then examined under a microscope by a pathologist responsible for the diagnosis to confirm the presence of cancer cells. Since the biopsy work requires comprehensive knowledge and technical proficiency, computer-aided diagnosis can assist radiologist and help in getting the results.

Initial clinical experiment has shown that medical robot has greater precision, faster execution and less risks of infection compared to handheld approaches in conducting breast biopsy (Rovetta, 2000). Some other possible advantages include less risk, pain, recovery time, cost-effective, reduce radiologist's fatigue and fewer needle placements to correctly sample the lump (V. Mallapragada et al., 2011; Nelson et al., 2010). Thus, an ideal case of medical assist equipment is to use robotic instruments with the knowledge and experience of the radiologist to pilot the robot. Clinical matters to be tackled involve positioning feedback to the operator via force feedback and image verification or a combination of sensor systems for sampling device insertion (Nelson et al., 2012). Nonetheless, concerns regarding large learning curves, lesser radiologist tactile feedback and reasonably high implementation cost will need to be confronted before widespread clinical approval is possible (Gerhardus, 2003).

Small incision during Fine Needle Aspiration Cytology (FNAC) of the breast is a minimally invasive procedure that resulted in a very limited Field of View (FOV) to the naked eyes of the radiologist. Hence, one of the most crucial instruments is an image guidance device such as an ultrasound transducer that can provide analytical information as to the nature of a breast lesion and the positional tip of the biopsy needle. At present, the radiologist has to hold both transducer and biopsy needle simultaneously as shown in Figure 1.1 to effectively conduct the Ultrasound-Guided Breast Biopsy (UGBB) procedure. However, even though handheld approaches can provide accurate sampling of breast lesions, accuracy differs from one radiologist to another (Salem et al., 2009). Besides, a precise localization gradually becomes further challenging for deeply located and smaller sized breast lesions even with exceptional training and high level of experience (Nelson et al., 2012).

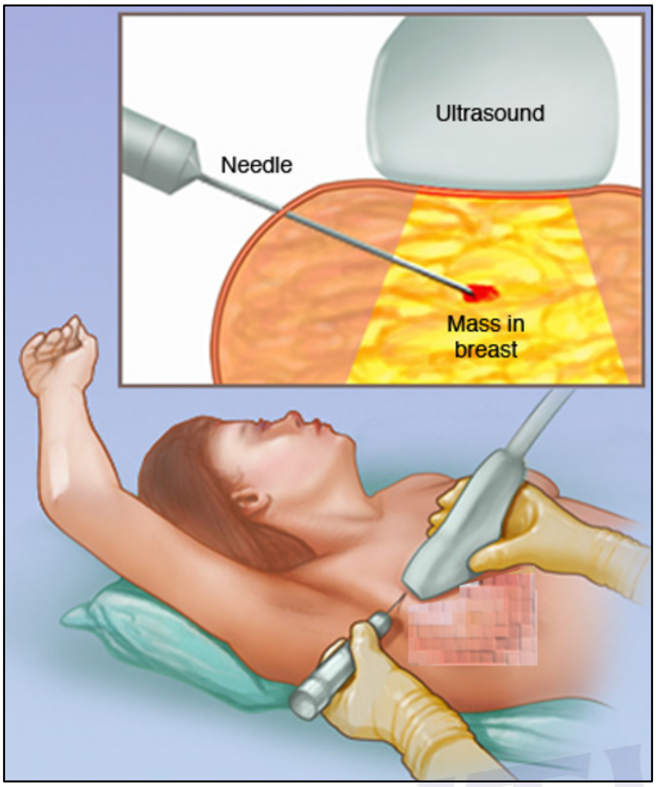

Figure 1.1: Ultrasound-guided core needle biopsy (Mayo Clinic, 2014)

During the UGBB procedure, the needle approach to the lesion has to be as parallel to the chest wall as possible in order to avoid the worst case scenario of a pneumothorax complication (collapsed lung) where it can be a serious life-threatening event (Apesteguía & Pina, 2011). Likewise, the orientation of the ultrasound transducer should be parallel to the needle as well to easily visualize the needle. Formerly, an Italian study of more than 200 000 breast biopsy procedures described that pneumothorax life-threatening complication occurred in 1 in 10 000 cases (0.01%) (Catania et al., 1993). However, the authors admitted that this figure might be underrated due to unrecognized and asymptomatic cases of pneumothoraxes.

Similar incident was first reported in 2005 to a woman having a mild form of Poland's syndrome (absence of chest muscle) (Salhab et al., 2005). Patients with deeply located central lesions and patients with thin bodies and small sized breasts are also at greater risk for developing this complication. As such, the handling of multiple devices simultaneously is believed to be one of the contributing factors that deteriorated radiologist skills in performing the biopsy procedure, thus leading to the pneumothorax complication.

Additionally, inconsistent contact forces from the ultrasound transducer to the breast can lead to repeatability problem for similar acquisition state and images of the same tissue region (Gilbertson & Anthony, 2015). The uncontrollable forces along with hand tremors from the radiologist encourage the suspected lump to move away from its original position. Even though the radiologist continuously tries to maintain constant forces, the slippery condition of the ultrasound gel makes it possible for the transducer to lose contact with the breast subsequently making the lump disappear from the ultrasound-imaging FOV. Furthermore, due to the dynamic structures of the breast tissue, large deformations occurred inside the breast whenever the biopsy needle is inserted (DiMaio & Salcudean, 2002; V. Mallapragada et al., 2008a). Ultimately, multiple insertions at the same biopsy region might be necessary to successfully sample the target which in return further compromising the integrity of the breast tissue.

Therefore, a robust hybrid force/position control of a UGBB robotic system for manoeuvring the ultrasound transducer is proposed in order to maintain low, safe and consistent contact force on the breast. By implementing this method, expected advantages include enabling full control on needle handling and higher concentration to the radiologist during lump sampling. Furthermore, other anticipated benefits include compensation for external disturbances to the UGBB robotic system, which offers the ability to indirectly track the position of the suspected lump and reducing the number of unnecessary needle insertion.

1.1 Problem Statement

Current researches and developments of UGBB robotic system are more focused on the enhancement of needle position and insertion, but rather neglect to address force and position control of the ultrasound transducer itself as a significant element (Hatano et al., 2011; Kobayashi et al., 2012; Liang et al., 2010; V. Mallapragada et al., 2011; Nelson et al., 2012; Okazawa et al., 2005). Radiologist has to handle multiple devices at once which could reduce the abilities in performing such procedure resulting in radiologist's fatigue, compromising the structural integrity of the breast tissue due to multiple insertions and susceptibilities to pneumothorax complication for the patient.

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